MECHANICS OF FORMATION OF ARCUATE MOUNTAINS

WILLIAM H. HOBBS
University of Michigan, Ann Arbor, Michigan

PART II

THE FOLDING PROCESS STUDIED IN THE PROFILE—GENERAL CONSIDERATIONS

Active and passive forces involved in folding.—So soon as we take up the mechanics of rock folding, we again encounter the vital question of the location relative to the fold of active and passive forces in the process. Among the Swiss geologists it is universally held that the active force (*Schub*) which caused the folding and slicing of the Alpine highland came from the southeast and was directed toward the northwest. This view would appear to rest upon the widely accepted notion that folds which are unsymmetrical have been produced by an active force which operated from *above* and *behind* the arch with the effect of pushing over the crown so that in later stages it overhangs the base. This conception is involved in the term "overturned fold" and its many variations.[1] If we may for the moment liken a fold to an overturned free wave upon the surface of a body of water—a so-called "white cap"—the active force which is generally assumed to produce the fold has the same direction relatively as the wind. Like the wave, the fold bends over toward the lee side because, as has been believed, the active force operates above and directly upon the arch of the fold, and not upon its base (Fig. 9, *a* and *b*). The effect of this system is a couple—two parallel forces of which one is in this case a passive force of resistance, which act in opposite directions and are separated by a certain distance referred to as the arm of the couple. In

[1] See Margerie et Heim, *Les dislocations de l'écorce terrestre, essai de définition et de nomenclature*, Zürich, 1898, p. 54. Dr. E. A. Smith has, however, given the name "underthrust folds," to what he evidently regards as exceptional cases of folding ("Underthrust Folds and Faults," *Am. Jour. Sci.* (3), XLV (1893), 305–6).

all such cases there is a tendency to produce rotation, as appears from the example of the water wave. So far as the *form* of the resulting fold is concerned, the result would be similar if the active and passive forces were to be reversed; and though conscious of an appearance of presumption in again opposing his own view to such weight of authority, the writer will endeavor to show not only that the principal active force involved in the folding of the Alps must have been directed from the northwest toward the southeast,[1] but that the mechanical difficulties which have stood in the way of a more general acceptance of the views of the Swiss geologists, with this modification in large measure disappear.

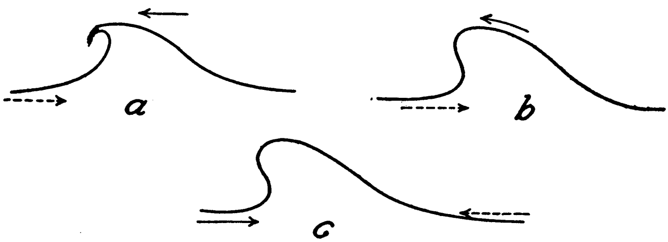


FIG. 9.—Diagrams to illustrate the active and passive forces involved in folding: *a*, position and direction of forces involved in the overturning of a free water wave; *b*, system of forces assumed by the Swiss geologists to account for the folding of the central Alps; *c*, the author's modification of this view.

It is of course to be understood that the active force tending to produce movement may not be solely from a single direction; but of the two opposed directions parallel to the chief compression, the active force as here understood is that one which represents the greater movement. If in Fig. 10 two active forces or thrusts[2] which tend to compress a given section of the earth's shell be represented in intensity by the distances a' and b, the active force which becomes effective in producing unsymmetrical flexures such

[1] Willis has expressed his opposition to the conception of overturning which is apparently the standard doctrine of the day ("The Mechanics of Appalachian Structure," *13th Ann. Rept. U.S. Geol. Surv.*, 1893, Pt. II, p. 233); see also W. H. Hobbs, *Earth Features*, New York, 1912, pp. 436–38.

[2] This term is not to be confused with that generally applied to the surface of failure in folds, which latter should, we believe, be abandoned for reasons which will be given below.

as are the rule in all much compressed mountain districts is the difference between the two forces, *c*. Had the active forces *a* and *b* been just equal and the beds under compression offered uniform resistance, the folds produced should be symmetrical, and in the end have constituted a series of vertical isoclinal flexures, which are as rare in nature as they would upon this assumption be expected to be (Fig. 11).[1] The lack of a fore-and-aft symmetry in mountain arcs clearly indicates that the radially directed thrusts are not in equilibrium, but that one notably overbalances the other.

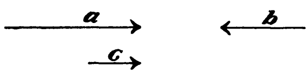


FIG. 10.—Diagram to illustrate the resultant of two parallel but opposed active forces, or that effective in producing unsymmetrical flexures.

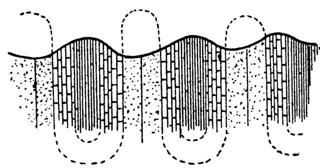


FIG. 11.—Vertical isoclinal folds

Incompetence of folding layers to transmit compressive stresses to long distances.—At the outset it is important to emphasize that the capacity of bodies to fold shows that they cannot transmit compressive stresses to long distances, due to the dissipation of energy in producing internal strains within the folding mass. With constant diminution of intensity, therefore, the active force is transmitted to certain moderate distances only from its place of application. Although perhaps self-evident, this fact has been demonstrated in experiments by Cadell, who has expressed its application to folding strata in the following sentence: "Horizontal pressure applied at one point is not propagated far forward into a mass of strata."[2] The distance to which the active force is carried

[1] This discussion obviously rests upon the assumption that the folding of any given district is due to forces from without the area itself, though independent of any special theory of planetary contraction. Any assumption which requires that the active force causing compression originate *within* the district itself requires a wholly different analysis. Thus the view of Mellard Reade, which conceives the cause of folding to be expansion by heat of areas of sediments due to depression and consequent rise (relative to the beds) of isogeotherms, would require that the active forces proceed outward toward relative rigid formations, and zones of folding should develop simultaneously on opposite margins of the more plastic interior area.

[2] Henry M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh*, XXV (1890), 356.

in sufficient intensity to produce appreciable deformation or folding may be referred to as the *reach*. In rock masses which offer a uniform resistance to folding throughout a given area, the limited reach determines that folds will begin to form upon the side which is toward the active force.[1] The very existence of an area which folds, surrounded by one which does not, implies that but for this central folding area the rock masses would be competent to transmit the tangential force without extensive deformation. The fact that folds first develop upon that side of the folding area which is toward the active force is amply demonstrated by simple experiments which were performed by Daubrée.[2] In these experiments a vertical section of the unyielding and encompassing area of the earth's shell was represented by a stiff piston-rod through which the active force was transmitted to a flexible leaden strip which therefore takes the place of the folding rock masses. When the strip of lead was made of uniform thickness, and hence of uniform strength, the folds within it formed first upon the side which was toward the piston. Only by thinning and thereby weakening the strip at the farther end could the folds be first produced at that end. The experiments of all later investigators working with materials and under conditions which must more nearly simulate those obtaining within the earth's shell have only confirmed the correctness of these simple deductions from Daubrée's experiments.

It is because of this limited reach of the deforming stress that anticlinoria which by construction imply the *simultaneous* development of similar and approximately equal anticlines throughout the length of a flatly extended arch of strata[3] are apparently unrealized in nature. Most of the supposed classical examples have been drawn from the Alps as represented upon old sections, and these may today be adequately explained upon the assumption of the development of *successive* anticlines as detailed below (p. 172).

The strength of rock formations as modified by temperature and load no doubt sets a definite limit upon the initial span of anticlines

[1] See note on Paulcke's experiments on p. 172.

[2] A. Daubrée, *Géologie expérimentale*, pp. 292–300.

[3] See, for example, Van Hise, *Principles of North American pre-Cambrian Geology*, pp. 608–9.

developed in series, and a fruitful inquiry would be to fix, by thorough examination of folded districts, the maximum span of fully disclosed, as against merely inferred, anticlinal arches.

Importance of lenses of sediments in inducing folding.—Lest too large importance be ascribed to local weakness of strata in fixing the location of initial folds, it is well to remember that folded areas do not appear to be those which are thinnest, but, on the contrary, that they are the thick lenses of sediments in which formations are present in fullest development—areas of continuous deposition in former epi-continental seas. The explanation of this fact is found in the peculiar cross-section of a lens of sediments. Obviously a perfectly straight rod of more or less rigid material whose axis is parallel to the direction of compression will transmit larger stresses than one which may be considerably thicker and stronger but is initially slightly bent from the direction of the compressive stress (Fig. 12, *a* and *b*). In the first instance (*a*), the applied force being directly opposed by the resistance, the rod tends merely to be slightly thickened, whereas in the second case (*b*), the active force is deflected parallel to the tangent to the curve, and at a rapidly accelerated rate this deflection is augmented with increasing pressure. It is thus easy to see that the cross-section of basins of deposition, being lenticular, may have been more important in favoring the location of folds than their greater thickness could have been as a hindrance. Willis, who discovered the importance in the location of folds of what he has called "initial dip," has thus stated the law of competent structure:

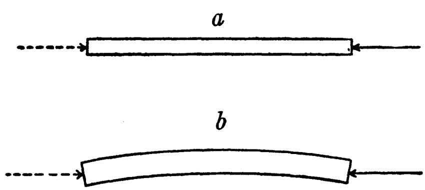


FIG. 12.—Diagram to illustrate the relative tendency to fold, or buckle, of: *a*, a straight rod; and *b*, a thicker but slightly curving rod.

> The transmission of pressure through a folding, stratified mass may be stated as follows: So long as the stratification is parallel to the original direction of pressure, the force is transmitted as a whole and tends to reduce the volume of the mass; when the strata are inclined to the direction of pressure the thrust is resolved into two components, the one parallel to the bedding, the other perpendicular to it; the former produces movement when it overcomes the

friction on bedding planes, the viscosity of the strata, and any opposing force, as that of the load; the latter becomes active when it can cause some part of the resisting mass to move. . . . .

In strata under load an anticline arises along a line of initial dip, when a thrust, sufficiently powerful to raise the load, is transmitted by a competent stratum. The resulting anticline supports the load as an arch, and being adequate to that duty it may be called a competent structure. From the conditions of the case it follows that none other than a competent structure can develop by bending. If the thrust be not powerful enough to raise the load there will be no uplift. . . . .[1]

What has been brought out above concerning the direction of the active force would indicate that, coming as it does from the ocean basins, the thrust, instead of being influenced by initial dip at the shoreward end of a section of epicontinental deposits (which should develop there an initial syncline), is received at the off-shore end of the section and should be first diverted upward by the steeper beds upon the continental slope and so yield an initial anticline. This is, moreover, more in harmony with the results of experiment.

It seems proper to speak of the competence of an arch or anticline as its capacity in any stage of formation to lift load resting upon it.[2]

In order to simulate rock folding under as nearly as possible natural conditions, Willis in his experiments made use of layers which were of nearly uniform thickness and strength throughout and which, though sufficiently rigid to be deformed by failure under ordinary testing conditions, became potentially plastic under the load of shot which was applied in the experiments. In confirmation of the results at which one arrives from a purely theoretical treatment of the subject, it is important to note that in all Willis's experiments except when special conditions were introduced, anticlines developed on the side of the mass toward the active force

[1] *The Mechanics of Appalachian Structure*, pp. 246, 250.

[2] It is little likely that, barring exceptional cases of small anticlines, a competent stratum can lift the entire load from beds beneath, as seems to have been implied by Willis. We should in that case approach to surface conditions within a well-cemented masonry arch in which the accelerated rate of increase of weight of arch relative to its strength sets such a low limit upon the span as to be prohibitive.

or thrust, and that in successive stages of its evolution the anticline became increasingly unsymmetrical with the axial plane dipping away from the active force and finally was underthrust in the same sense. In recent experiments by Paulcke[1] which were carried out with the idea of simulating Alpine tectonics, ***but with the presupposition that there had been overthrusting from behind the anticlines***, the arches were in normal cases generally either bent over toward the active (moving) force, or else a stiff plate (*Druckplatte*) was introduced and prevented their natural manner of deformation.

From the nature of rock materials we conceive that folds develop within a zone probably some miles below the earth's surface, since we believe that at such depths only can the rocks become sufficiently plastic under their load. Nearer the surface rock materials, which are normally highly elastic, must be deformed by failure or fracture, and over a rising anticline must be adjusted in block sections whose movements become manifest at the surface in earth shocks or quakes (note conditions in Bonin arc, p. 79).

A consequence of the studies by Adams, which have for the first time revealed the enormous hydrostatic compressive strengths of rocks, is certain to be a modified conception of the zone of flow (better, zone of folding) within the earth's surface shell. To assume that more than eleven miles of sediments have been eroded from those folded beds which outcrop at the earth's surface must make the hardiest theorist pause and consider whether the closing of pores necessary to permit of folding may not be due to an excess of tangential compressive force over that of the radially directed load—or, in other words, that hydrostatic conditions of compression were seldom realized in the folding of those strata, at least, which we find exposed at the earth's surface.

THE FOLDING PROCESS STUDIED IN THE PROFILE—ANTICLINE EVOLUTION

Successive sectional curves of a growing anticline.—Since, when the anticline begins to rise, the radial component of the compressive stress has the least value, and the tangential component the

[1] W. Paulcke, "Das Experiment in der Geologie," *Festschrift z. Feier des Geburtstags Seine Kön. Hoheit*, etc., herausg. v. d. Tech. Hochschule, Karlsruhe, 1912, pp. 108, figs. 44 and pls. 29. Note the *Druckplatte* in the apparatus which is figured in Pl. 8.

greatest, the span of the arch must at that time be a maximum.[1] The point from which the arch springs upon the side away from the active force thus becomes established as an abutment, so to speak, and the length of the arch is maintained constant up to a limiting stage to be presently discussed. The general shapes of simple anticlines of increasing asymmetry are well known upon the basis of experience, and the attempt has here been made to represent successive stages arbitrarily spaced in the process of anticline evolution. Six of these belong in the class denominated unsymmetrical, whereas the remaining three are "overturned" (Fig. 13). Throughout, the assumptions have been made: first, that failure of the arch does not take place; and, second, that its length remains constant—a condition which would often be realized in nature for the first six cases, but could hardly persist long after underturning had set in.

Professor Theodore R. Running of the University of Michigan, an expert in the mathematical study of curves, has at the writer's request subjected this series of curves to examination. He has found that to a close approximation the first seven of the series, the only ones which were tested, alike possess an axial line[2] which bisects all horizontal chords, and that the seven may be fitted to the comparatively simple general equation

$$y=y^{0}\left(\frac{a^{2}-x^{2}}{a^{2}}\right)^{m}$$

in which the oblique co-ordinate axes are the base line and the bisecting axial line, in which y^{0} is the length of this axial line from base to crown, and in which a is one-half the base.

Competence of a relatively strong member in an anticline to lift the load from inferior strata.—For the purposes of this discussion, the load which rests upon an anticline in competent strata may be

[1] Cf. Willis, *op. cit.*, pp. 251–52.

[2] Trace of the axial plane of the anticline. That this axial plane bisects horizontal chords of the anticline in all stages has been often noted by the writer in studying the folded schists of the Berkshire Hills of New England and elsewhere; but this character had not consciously been made a basis of measurement in drawing the curves of Fig. 13, which were made to accord with the *shapes* of anticline sections repeatedly observed in the field.

regarded as uniformly distributed throughout a horizontal plane; since, as already stated, anticline formation is believed to occur at such depths that the altitude of the arch is small by comparison. The discussion of the competence of an anticline differs from that of an arch of masonry, for the reason that the latter receives no external support in a vertical direction except at the abutments. An anticline is, upon the other hand, in part supported by the resistance to compression of the weaker formations which are arched beneath it. It may never alone support the entire load which rests upon it; but since it is stronger than immediately inferior beds, it tends always to lift from them some portion of the load. This portion varies at different parts of the arch, and for any point is roughly proportional to the cosine of the angle which the tangent at that point makes with the vertical (Fig. 14). By a summation of these values for

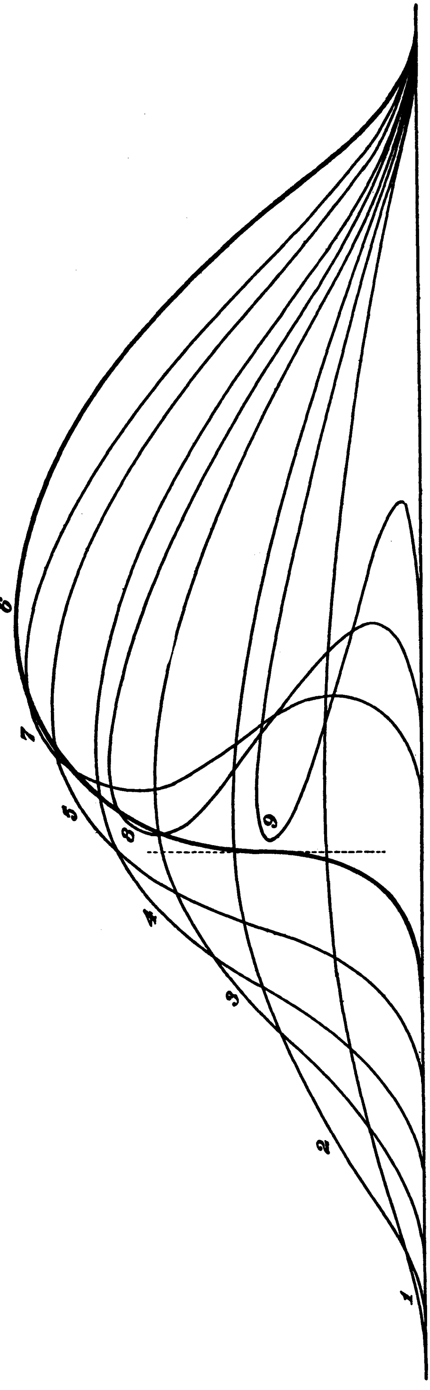


FIG. 13.—Series of successive stages of an anticline developed in a competent member within a folding series. The active force is at the left.

the entire arch a figure is obtained represented by the area *AGOHB*, which for convenience we may refer to as the "cosine area." To this there is probably to be added for the crown region particularly some part of the tangent-normal component of the load which is spent in internal strain within the arch; but since any extensive settling of the crown would bear upon the subjacent formation and transmit this burden to them, the additional amount from this source is probably so small as to be negligible in our discussion. For the different stages which we have selected in the evolution of an anticline, these cosine areas may be derived by graphical methods, and through dividing each by the total load, the percentage which is lifted by the competent member may in each case be roughly estimated.

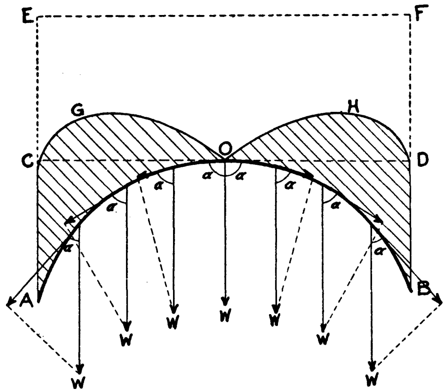


FIG. 14.—Diagram to show the proportion of total load which is lifted from underlying formations by an anticline here assumed for convenience to be the arc of a circle. *AOB*, anticline; *CDEF*, area proportional to the entire load; *AGOHB*, cosine area proportional to the load lifted from interior formation beneath the arch.

Relative competence of a member in successive stages of anticline evolution.—The cosine areas for each of the successive stages of a developing anticline which are represented in our series afford the figures of the following table:

TABLE I

Stage	Ratio of Rise to Span	Competence Figures	Percentage of the Load Lifted	Relative Volume of Anticline
1	0.073	12.6	12.6	8.6
2	.152	25.6	26.9	15.0
3	.223	34.5	37.8	19.0
4	.301	37.2	43.5	21.8
5	.361	37.8	47.9	22.8
6	.441	36.5	51.9	24.5
7	.578	29.6	50.9	18.5
8	.471	22.4	37.2	11.8
9	0.274	3.6	7.9	5.2

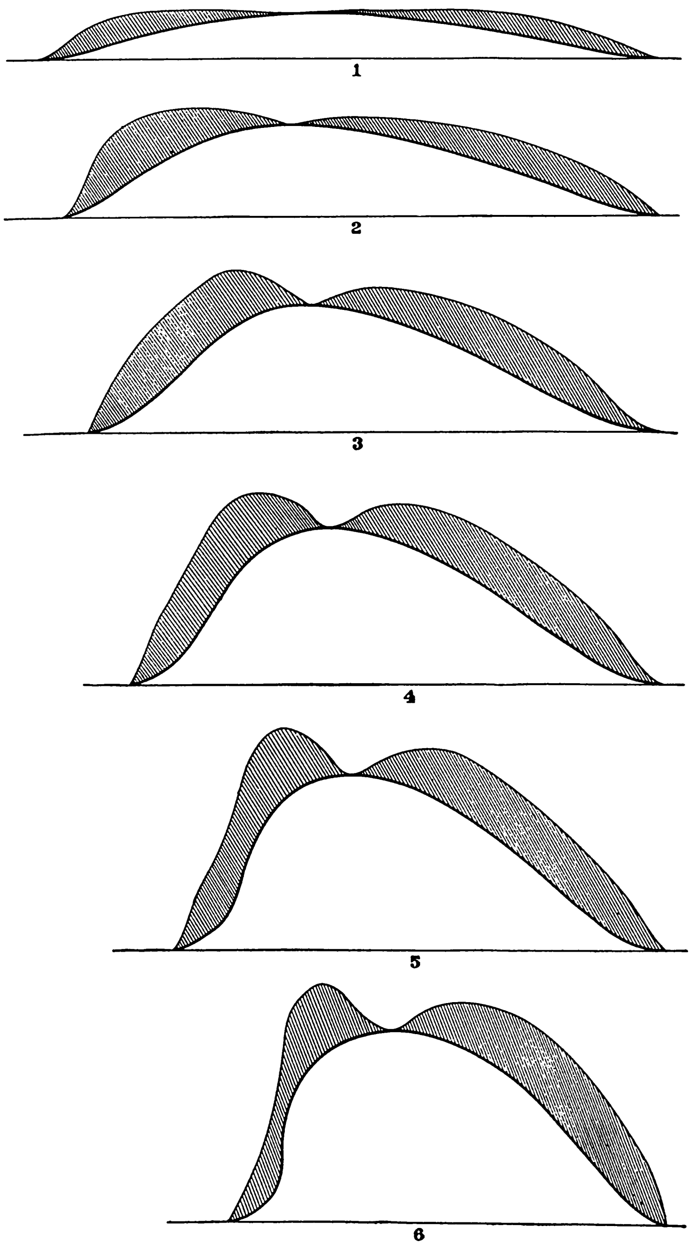


FIG. 15.—Cosine areas of the arbitrary stages 1 to 6 of a growing anticline

The drawings upon which these figures are based have been reproduced on a much reduced scale in Figs. 15 and 16. From examination of them it is learned that an anticline within a com-

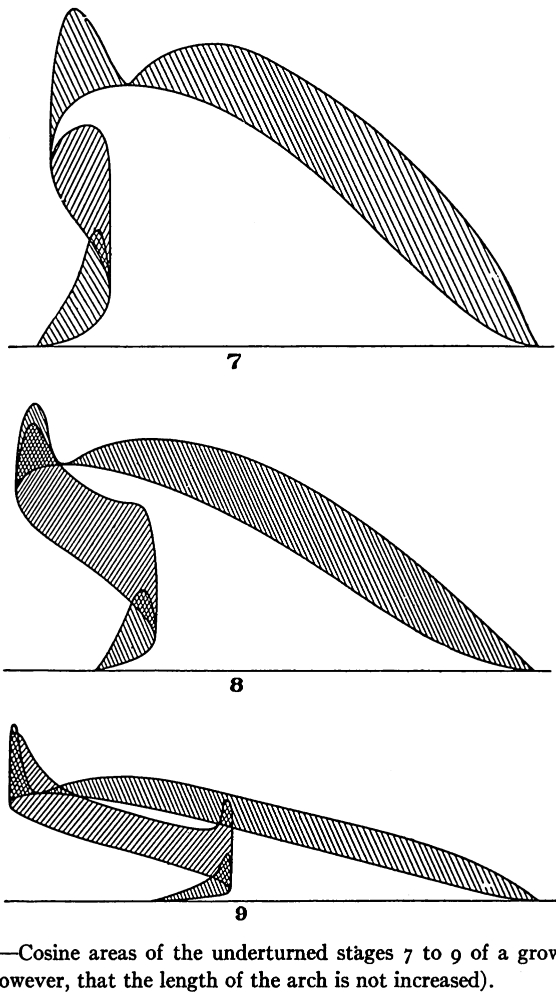


FIG. 16.—Cosine areas of the underturned stages 7 to 9 of a growing anticline (assuming, however, that the length of the arch is not increased).

petent stratum is able in its early stages, when the ratio of rise to span is relatively small, to lift but a small proportion of its load from the underlying formation; but that this competency increases beyond the arbitrary stage 1, in which the ratio of rise to span

is about $\frac{1}{10}$. Although the actual load lifted increases but little after this ratio has reached $\frac{1}{4}$, the percentage which is lifted of the total load upon the arch continues to increase up to stage 6, where underturning begins and from which point the competence falls off at a rapid rate. These deductions are graphically reproduced in Fig. 17, where the abscissae are the ratios of rise to span, and the ordinates have a different significance for each curve. The upper curve gives the percentage of total load which is lifted from inferior

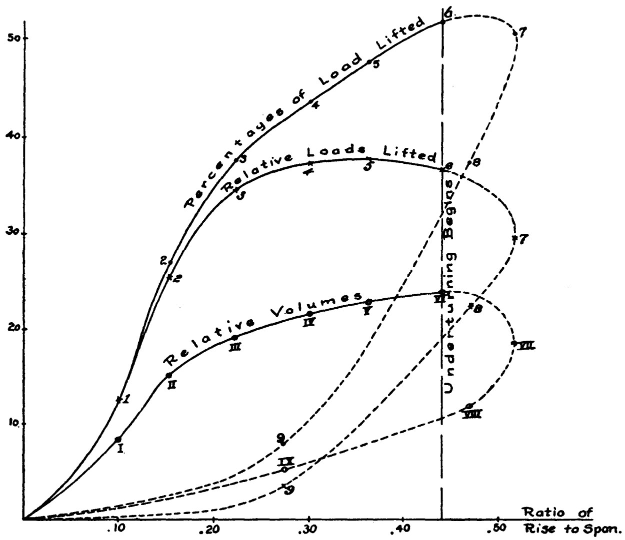


FIG. 17.—The curves of relative competency and of relative volume of an anticline in different stages up to the stage of underturning; and (in dotted lines) the purely hypothetical competence and volume on the assumption that the length of the arch is not increased after extended underturning without failure.

beds within the arch; the middle curve gives in arbitrary units the relative loads which are lifted; while the lowest curve gives in arbitrary units (not those of the middle curve) the relative volumes inclosed by the anticline.

Initiation of new anticlines in series.—The stage marked 6 in our series is where underturning begins, for the steeper limb includes a point at which the tangent to the curve is vertical. The active compressive force, which up to this stage has been deflected upward

and hence devoted to lifting the load, can no longer be thus turned out of its original course and is therefore more or less completely transmitted through the anticline to the still unfolded section of the stratum beyond (Fig. 18). At this point, therefore, the anticline has the effect of temporarily at least stiffening the stratum locally and so extending the reach of the deforming stress. Since, however, some energy is lost in the continued deformation of the original anticline, the new reach beyond the farther base will generally be less than that when the first anticline began to rise. A second arch thus tends to form behind the first, but one of somewhat smaller dimensions.

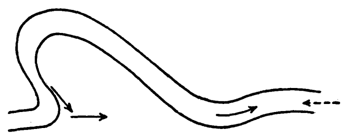


FIG. 18.—Diagram to illustrate the initiation of new anticlines in series.

This second anticline having in its turn risen to the stage of underturning, conditions for the development of a third enter; and the process may go on until continued diminution of the reach due to imperfect stiffness of the anticline series brings the process to an end.

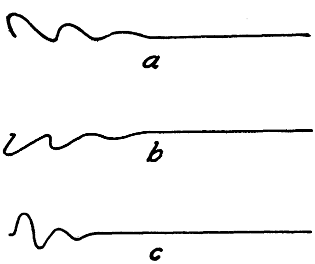


FIG. 19.—Correct (*a*) and two incorrect (*b* and *c*) representations of anticlinoria.

Successive anticlines thus developed in series are characteristic of Willis's experiments so often cited, and may be represented schematically by *a* in Fig. 19, where anticlines and synclines alike are developed *above* the original position of the stratum. Thus it is seen that though *series of arcs* develop in order from the central area of the series outward, the *series of anticlines* within each arc develop in the reverse order, or from without inward toward the central area.

Conditions of formation of plunging crowns and recumbent folds.—The peculiar curves of unsymmetrical anticlines show clearly that the horizontal external forces which produce them are so resolved as to produce rotation, and in such a sense that the base of the arch is pushed backward under the crown. This is equivalent to saying

that after the anticline has begun to rise, a couple arm separates the two opposing forces and that the point of application of the active force of compression is below that of the passive force of resistance. So soon, however, as underturning has set in, a new couple enters which involves not the compressive forces in generally horizontal positions, but the vertical external forces; namely, the load and the passive resistance of the mass to depression (Fig. 20). Within the underturned portion of the anticline this passive force

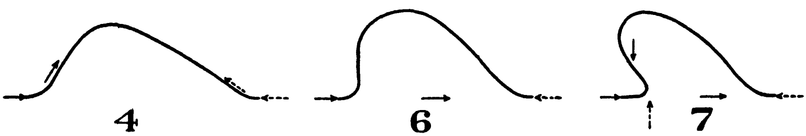


FIG. 20.—Diagrams to show the new couple which enters with the underturning of anticlines.

may be concentrated near the base of the under limb, while the load upon the underturned section of the arch is centered in front, so that the action of the couple tends to rotate the crown of the arch, not forward as before, but downward. Such sinking of the crown is resisted by any support of the superior strata which have been underfolded beneath the crown. If these are of sufficiently strong material, the crown is not bent; but in the event of their being weak, the crown is sunk as in Fig. 21. Such "plunging crowns" (*tête plongeante, sinkende Gewölbe*) are the normal feature in the northern zone of the Alps, where the weak Flysch (Eocene) overlies the competent Helvetian limestones.[1]

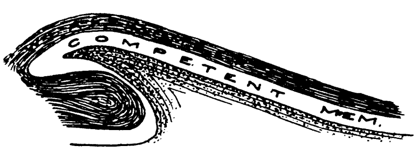


FIG. 21.—Plunging or sinking crown of an underturned anticline due to weak strata above the competent member.

Whether the crown be sunk or not, as the anticline becomes increasingly underturned, it is forced down as a whole by the action of this couple and so becomes a "recumbent fold" (Fig. 13, stage 9).

[1] For another excellent example of a plunging anticline crown see E. B. Bailey and M. Macgregor, "The Glen Orchy Anticline," *Quar. Jour. Geol. Soc.*, LXVIII (1912), 164–78, Pl. 10, and especially Fig. 3.

Attenuation of under limb of anticline after underturning.—There are still other consequences of the rapid loss of competence of an anticline after underturning has begun. The active force of compression, now no longer deflected upward into the first anticline but transmitted along its original direction, tends to reduce the volume of the included arches of inferior strata. The resistance which they offer to this reduction of volume tends to extend (stretch) the under limb (Fig. 22). It is a very general observation that thinning of the under limb is characteristic of so-called "overturned" anticlines, and emphasis may here be laid upon the point that, were anticlines really overturned, as has been so generally supposed, it is the upper limb which should be attenuated by the process, and not the lower (Fig. 23).[1]

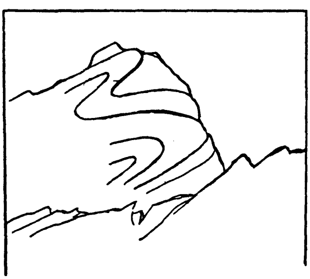


FIG. 22.—Stretched under limb of a recumbent anticline. Drawn from a photograph of the Dent de Morcles as seen from Les Martinets, western Switzerland.

Though closed anticlines with attenuated upper limbs have, so far as known, never been observed in folded rock formations, they are, on the other hand, the characteristic type of close recumbent folds in the ice of glacier snouts, where the action of gravity and the resistance of friction in the lower layers force the upper layers to override the lower in true overturning movements (Fig. 24, p. 182).[2]

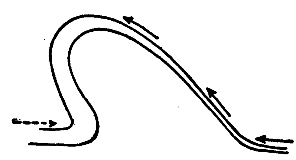


FIG. 23.—Attenuated upper limb of an anticline, a necessary consequence of overturning.

Not only may the lower limb of underturned anticlines be attenuated by stretching due to the resistance of the inclosed inferior strata, but the upper limb may in this stage be bulged upward as a result of the same system of forces.

[1] See also *ante*, p. 82, and Fig. 7. The sinking of the crown in an anticline tends to develop a tension within the upper limb, and it is perhaps conceivable that this tendency might in some stage either equal or overbalance that which normally causes attenuation of the lower limb, yet so far as known no example is furnished by folded strata.

[2] See among other views which show this effect: *Med. om. Gronland*, XLVI (1912), Fig. 24; *The Alpine Journal*, London, XXI, 187; Chamberlin and Salisbury, *Geology* I, 280, Fig. 268.

Possible formation of a magma macula beneath an anticline.—From examination of Fig. 17 and Table I (pp. 178 and 175) it will be seen that a relatively competent member near the top of a series of beds may remove from underlying members as much as one-half of the load which rests upon the arch. Under such conditions the underlying beds may be deformed by failure, even though the competent member is not (Fig. 25), and if at a depth where the isogeotherms are sufficiently high to melt the inferior members when thus partially relieved of load, a macula of magma may develop from the fused sediments. Such fusion is the more likely to occur

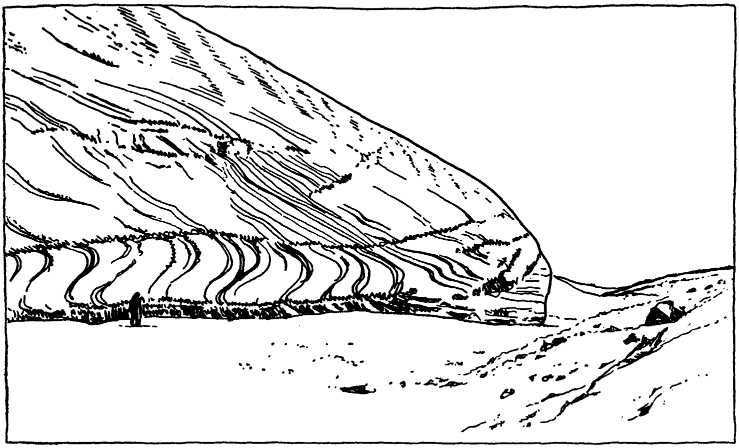
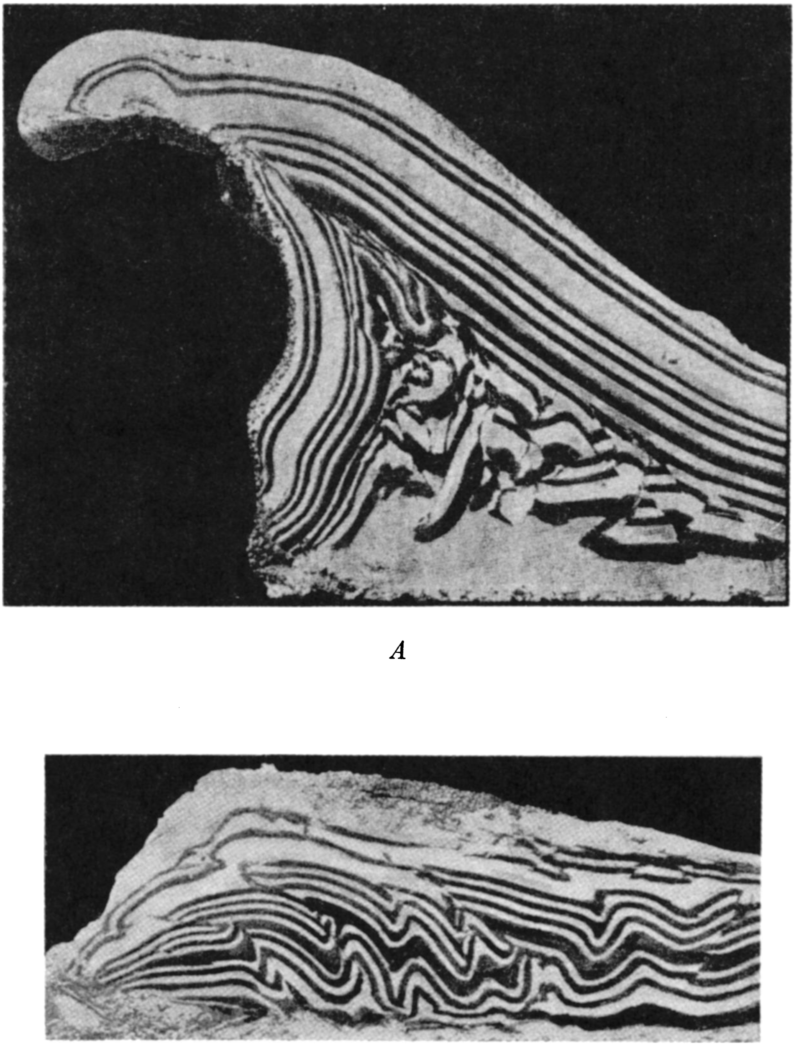


FIG. 24.—View of the front of the ice in northeast Greenland where overturned anticlines with thinned upper limbs are to be seen (after Koch and Wegener).

the lower the fusion interval of these inferior formations. The writer has elsewhere shown that the composition of igneous rocks in general is such that magma must inevitably develop, if at all, from the pelitic sediments, like shale and slate; the great abundance of which, no less than their structural weakness and their normal position in sedimentary series, is in favor of the view.[1]

Reduction of volume of anticline an efficient cause of elevation of magma.—Before the formation of a macula of magma through fusion

[1] "Some Considerations Concerning the Place and the Origin of Magma Maculae," *Gerland's Beiträge zur Geophysik*, XII (1913), 329–61, Figs. 1–8; see also "Variations in Composition of Pelitic Sediments in Relation to Magmatic Differentiation," *Comptes rendus 12me Congrès Géologique International*, Canada, 1913.



A

B

FIG. 25.—Results of lateral compression of parallel horizontal layers of materials which have varying degrees of rigidity, but are rendered plastic by the loads upon them. The active force is applied at the left (after experiments by Bailey Willis).

A, relatively less rigid beds deformed by failure beneath a competent (more rigid) stratum. There is also to be observed a slide which passes through all members alike.

B, successive anticlines and slides—imbricated structure.

of the roll of sediments beneath a relatively competent member, these inferior sediments support, as we have seen, a considerable portion of the entire superincumbent load. After fusion this support to the competent arch, which has hitherto been in excess of half the load, is now replaced by the molten magma of high incompressibility and perhaps also high viscosity. The compressive stress is now exerted through the under limb of the anticline in such a way as to squeeze or compress the macula. Under this action the under limb may suffer greater or less extension and consequent attenuation, but there must also be a tendency for the mass of magma to find an outlet along the path of least resistance, and it may in consequence fuse a course for itself upward toward the earth's surface (Fig. 26). In the upper levels any fractures that

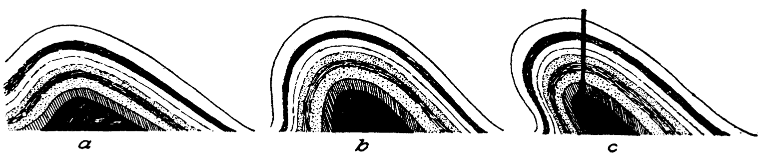


FIG. 26.—Diagrams to illustrate the tendency to reduction in the volume of progressively underturned anticlines and a consequent cause of the elevation of lava toward the earth's surface.

may exist are likely to be followed, and more especially fracture intersections. Recent studies make clear that magmas have the capacity of melting their own way by the process of overhead stoping. If such magma arrives at the surface along essentially vertical paths, its loci of emergence will constitute a series of arcs parallel to, and generally behind, the folded mountain arcs beneath which the maculae were developed. Thus we encounter in a consideration of the mechanics of folded mountain arcs a possible explanation of the position of volcanic arcs, and a possible solution of the vexed problem of the cause of elevation of magma in volcanoes of markedly Pacific type.

Volcanic vents once secured at the surface, magma should be exuded or ejected, and partial and further temporary relief be secured below from the compressive stress. Broad relationships

—rather than close responses— should therefore be expected to connect the growth of mountains and their attendant seismic disturbances with volcanic manifestations. The variations in the competence of the rising arch particularly after underturning has begun, considered in connection with the incidents of failure and their attendant consequences (hereafter to be discussed), are such as to make probable long-period variations particularly, both in seismic disturbance and in volcanic extravasation.

Backfolding of anticlines.—As yet comparatively little attention has been given by geologists to the effect of the local occurrence of weak or strong facies of a formation or series upon the character of the folds produced in them.[1] The subject is too complex and too little known to be discussed at length, but there are yet some

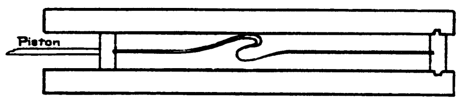


FIG. 27.—Backfold induced in a leaden strip above a local zone of weakness (after Daubrée's experiment).

very significant indications of its importance in fixing the location of the rare backfolds which have sometimes been described. In this connection a simple experiment by Daubrée is illuminating.[2] The strip of lead, which in so many of his tests was compressed from the end by a piston, was in one case locally weakened by thinning at some distance from the piston head, and the amplitude of upward deflection was limited by a horizontal beam above. The flexible strip was under these conditions deformed into a true backfold (Fig. 27), although it failed to simulate the Glarus double-fold as had been intended.

Nature has furnished an even better illustration in the Weissenstein of the Chain Jura, which the series of parallel profiles by

[1] Paulcke's experiments fail to afford altogether satisfactory results for the reason that his competent member is insufficiently loaded and does not fold.

[2] *Op. cit.*, p. 296, Fig. 85.

Buxtorf displays to the best possible advantage.[1] In these profiles (Fig. 28) the western (lower) ones reveal a slightly underturned anticline with perhaps some late bulging-upward of the upper limb,

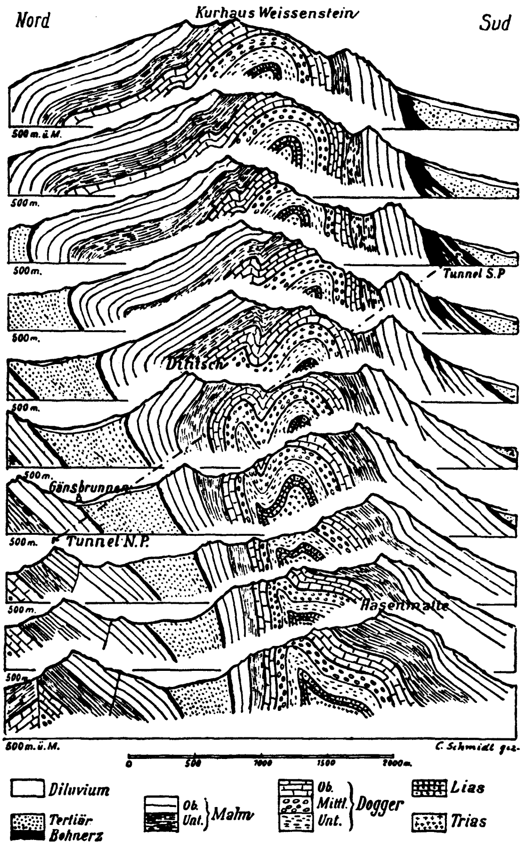


FIG. 28.—Series of geological profiles through the Weissenstein, Chain Jura, showing the development of a backfold above the *Bohnerzformation*, which is represented in black (after Buxtorf).

but with no indication of backfolding. Farther to the eastward, however, where a thin zone of the *Bohnerz formation* in part replaces

[1] Aug. Buxtorf, "Geologische Beschreibung des Weissensteintunnels und seine Umgebung," *Beitr. z. Geol. Karte d. Schweiz*, N.F., XXI (1907); C. Schmidt, A. Buxtorf, und H. Preiswerk, *Führer zu den Exkursionen der deutsch. geolog. Gesellschaft im südl. Schwarzwald, im Jura und in den Alpen*, 1907, pp. 21–22.

the strong Malm of the competent arch, the anticline is backfolded and in a degree dependent upon the thickness of the weaker formation.

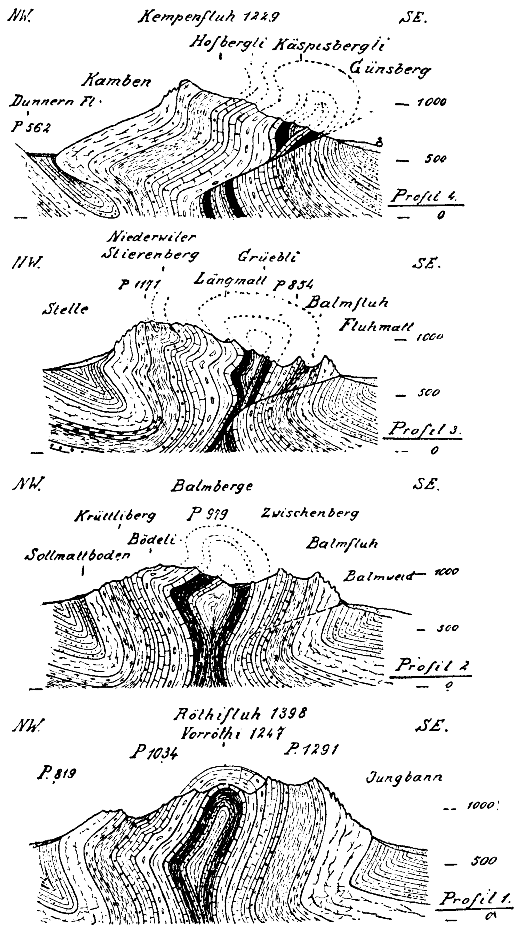


FIG. 29.—Backfolding due to the presence of a disjunctive surface in the folding formations. Series of profiles through the Weissenstein, Chain Jura (after Buxtorf).

The same district of the Weissenstein folds has supplied an equally instructive example of backfolding (near Balmberg-Günsberg), but one where the determining local weakness was a plane of fracture and not a zone of weak rock (Fig. 29).

Fan (carinate) anticlines may thus be a result of backfolding, though they may possibly in other cases be due to compression under the action of equal thrusts from opposite directions. It is, on the other hand, extremely difficult to conceive of conditions which could give rise to a fan or carinate syncline, for the reason that synclines, like anticlines, should develop above the zone of maximum pinch (see Fig. 19, p. 179). It is thus with a certain satisfaction that we may contemplate the abandonment of the conception of the Glarus double-fold, which in an earlier generation was standard doctrine in tectonics and required us to account for supposed fan synclines upon a gigantic scale (see *ante*, Fig. 1, p. 76).